Periodic magnetospheric substorms during fluctuating interplanetary magnetic field B_z

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[1] We study the possible role played by sudden changes in the solar wind in triggering substorm onsets. We show that periodic substorms can occur when the IMF B_z is small and fluctuating between southward and northward. The period of the substorms during the fluctuating IMF is ~3 hours, nearly the same as that during strongly and continuously southward IMF. We also show that large sudden changes in the solar wind do not necessarily trigger substorm onsets. For example, a northward IMF turning with a change of 31 nT in the IMF B_z after 1.2 hours of strongly southward IMF (between −12 and −18 nT) did not cause a substorm onset. The observations show that the period of substorms is not controlled either directly by variations in the solar wind or indirectly by the energy transferred to the magnetosphere from the solar wind. We suggest that a sudden change in the solar wind can trigger a substorm onset if and only if the magnetosphere has reached a state conducive to the generation of substorms. Substorms will occur every ~3 hours, no matter whether the IMF is continuously southward or fluctuating between southward and northward. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2744 Magnetospheric Physics: Magnetotail. **Citation:** Huang, C.-S., G. Le, and G. D. Reeves (2004), Periodic magnetospheric substorms during fluctuating interplanetary magnetic field B_z, *Geophys. Res. Lett.*, *31*, L14801, doi:10.1029/2004GL020180.

1. Introduction

[2] There has been a growing interest in periodic magnetospheric substorms [*Huang*, 2002; *Huang et al.*, 2003a, 2003b; *Reeves et al.*, 2004]. Periodic substorms last for many (e.g., 6–10) cycles, show well-defined waveforms, and have nearly constant periods of 2–3 hours. Multiple space-based and ground-based instrumental measurements show that each cycle of periodic substorms has all well-known characteristics of an isolated substorm. The periodic substorms studied by *Huang* [2002], *Huang et al.* [2003a, 2003b], and *Reeves et al.* [2004] occurred during continuously southward IMF. The first cycle of the periodic substorms might be related to a solar wind pressure impulse, while the subsequent cycles could occur under stable solar wind conditions. The observations show that the period of the substorms was not determined by the solar wind. *Huang et al.* [2003b] suggest that magnetospheric substorms have an intrinsic cycle time of 2–3 hours. After being excited, periodic substorms can last for many cycles without requirement of continuous external triggering. Each cycle of the substorms does not have to be triggered by an IMF northward turning or by a solar wind pressure impulse.

[3] On the other hand, the onset of isolated substorms is often correlated with an IMF northward turning or a solar wind pressure impulse [*Cann et al.*, 1977; *Kokubun et al.*, 1977; *Petrinec and Russell*, 1996]. Isolated substorms can also occur when there is no obvious triggering from the solar wind. *McPherron et al.* [1986] conclude that the expansion onset is an internal magnetospheric process and that the internal process can be influenced by IMF northward turnings or solar wind pressure impulses. The coincidence of the onsets of isolated substorms with sudden changes in the solar wind makes it difficult to identify the effect of the solar wind.

[4] In this paper, we present observations for the first time that periodic substorms can occur during fluctuating IMF and that the period of the substorms is still ~3 hours. No extra substorm onsets occur between two successive cycles even if a large change in the solar wind impinges on the magnetosphere. We will discuss the interpretation and implication of the observed phenomena.

2. Possible Effects of IMF Northward Turnings on Substorm Onsets

[5] We first present an example of periodic substorms under stable solar wind conditions. A magnetic storm started at 12 UT on 17 April 2002, and periodic substorms occurred on the whole day of 18 April during the initial recovery stage of the storm. Figure 1 shows the energetic electron fluxes measured by the Los Alamos National Laboratory (LANL) geosynchronous satellite 1990-095 on 18 April 2002. A prominent feature in Figure 1 is the periodic variations in the fluxes with a mean period of 2.7 hours. Such flux variations are termed sawtooth injections because of their shape. This case has been analyzed in detail by *Huang* [2002] and *Huang et al.* [2003a]. There is a one-to-one correspondence among each cycle of the near-tail magnetic reconnection onsets, each increase in the energetic electron fluxes at geosynchronous orbit, and other magnetospheric-ionospheric substorm signatures. Because the relationship between the sawtooth injections and other substorm signatures has been established by *Huang et al.* [2003a], we will use the flux injections alone to represent substorm onsets in this paper. The IMF B_z component was continuously negative and very stable. This case shows the characteristics of periodic substorms during stable IMF.

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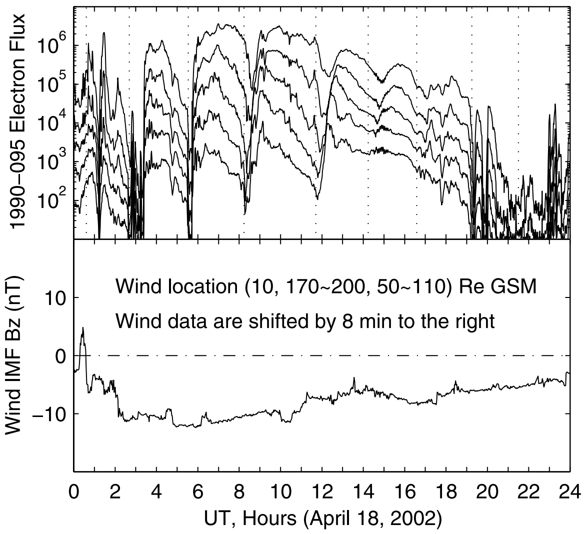

Figure 1. Electron fluxes measured by the LANL 1990-095 satellite and interplanetary magnetic field (IMF) B_z component measured by the Wind satellite on 18 April 2002. The electron energy channels are 50–75, 75–105, 105–150, 150–225, and 225–315 keV. The vertical dotted lines indicate flux injections (substorm onsets).

[6] We now present observations of periodic substorms when the IMF shows large variations. Figure 2a displays the electron fluxes measured by the geosynchronous satellite LANL-01A (MLT = UT + 0.5 hours) and the magnetospheric magnetic elevation angle measured by GOES 8 (MLT = UT− 5 hours) on 18 April 2001. The magnetospheric magnetic field is highly stretched during the growth phase of substorms and suddenly becomes more dipolar after the substorm onset. The dipolarization is characterized by the magnetic field elevation in the plasmasheet; the elevation angle is defined as $\tan^{-1}(B_z/(B_x^2 + B_y^2)^{1/2})$. There were three major increases in the fluxes and elevation angle at 0047, 0306, and 0600 UT. The flux increases represent the energetic plasma particle injections at substorm onsets, and the elevation angle increases represent the corresponding magnetic dipolarization. The periodic substorms occurred during the main phase of a magnetic storm.

[7] Figure 2b shows the solar wind pressure and IMF B_z measured by the Wind and Geotail satellites. Wind was located at (5, −244, −100) R_E GSM, and Geotail was at (−16, 21, 10) R_E GSM. Wind was in the solar wind because of its large distance in the Y and Z directions. The similarity in the measurements of the two satellites indicates that Geotail was in the solar wind too. The magnitude of the Geotail IMF B_z was larger than that of the Wind IMF B_z by a factor of 2, which is the effect of the bowshock. The first substorm onset at 0047 UT was correlated with a sudden increase in the solar wind pressure, the second onset at 0306 UT was not related to any obvious changes in the solar wind, and a third one occurred at 0600 UT. The most interesting and surprising phenomenon is that there was no substorm onset at 0418 UT when the IMF B_z suddenly turned from strongly southward (−18 nT) to strongly northward (13 nT). The change in the IMF B_z was as large as 31 nT in the Wind measurement (the corresponding change in the Geotail IMF B_z was 62 nT). In addition, the large solar wind pressure impulse at 0500 UT also did not cause a substorm onset. The IMF B_z had been strongly negative (−12 ∼ −18 nT) since the second onset at 0306 UT. However, neither the large northward IMF turning at 0418 UT after 1.2-hour southward IMF nor the solar wind pressure impulse at 0500 UT triggered a substorm onset. The next substorm onset occurred at 0600 UT, ∼3 hours after the second one. The 3-hour separation is typical between two cycles of periodic substorms. The results suggest that a sudden change in the solar wind cannot trigger an extra onset between two successive cycles of substorms.

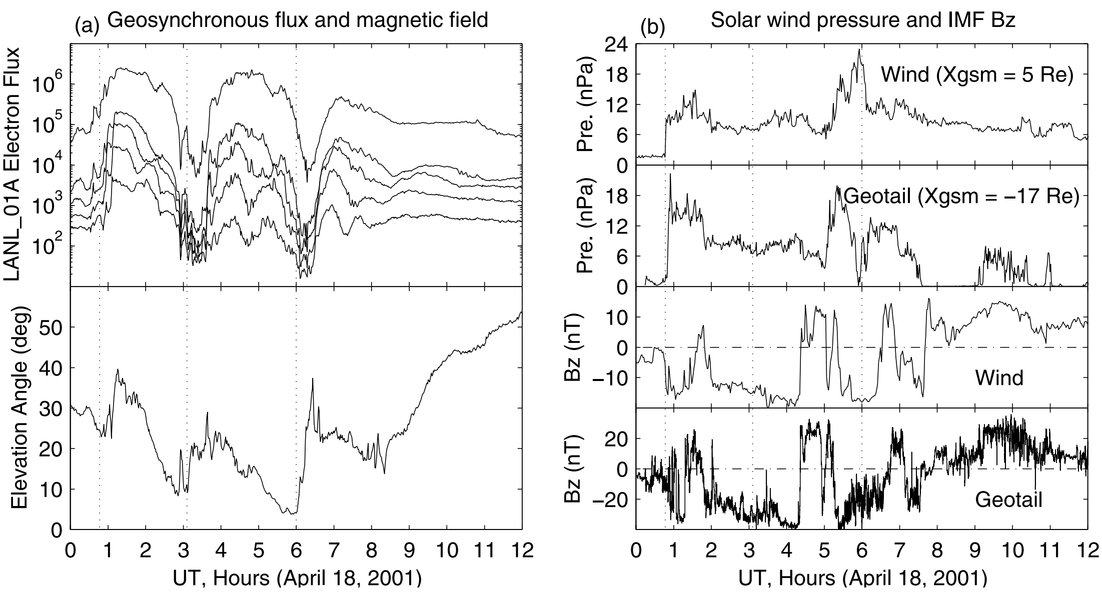

Figure 2. (a) Electron fluxes measured by the LANL-01A satellite and magnetospheric magnetic field elevation angle measured by the GOES 8 satellite on 18 April 2001. The vertical dotted lines indicate substorm onsets. Figure 2b shows the solar wind pressure and IMF B_z measured by the Wind and Geotail satellites. No time shift is used in Figure 2b.

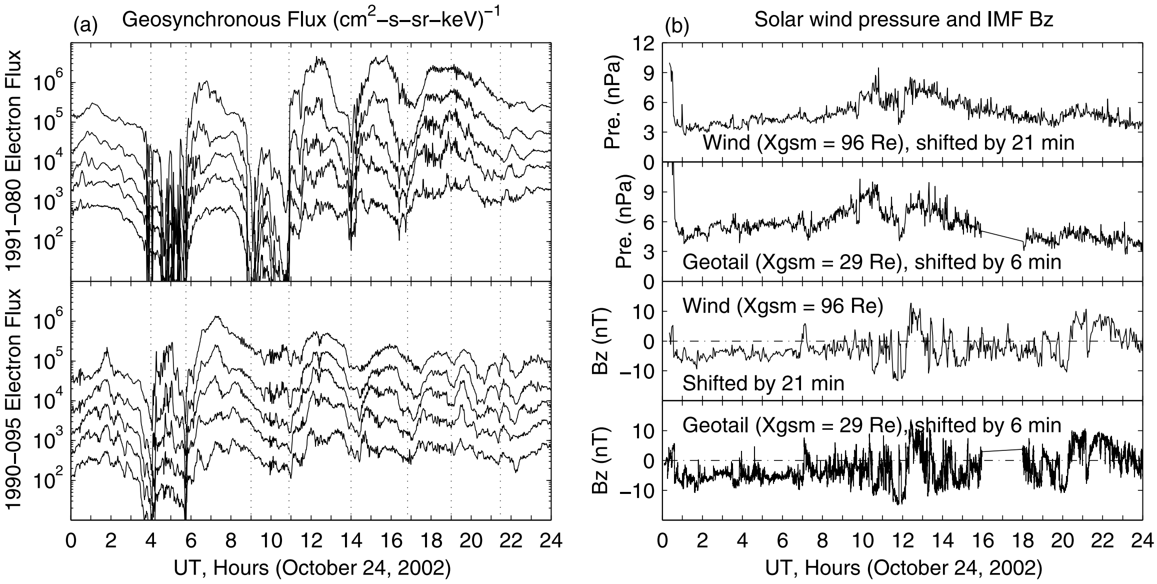

Figure 3. (a) Electron fluxes measured by the LANL 1991-080 and 1990-095 satellites on 24 October 2002. The vertical dotted lines indicate flux injections (substorm onsets). Figure 3b shows the solar wind pressure and IMF B_z measured by the Wind and Geotail satellites.

[8] Figure 3 shows a case in which the IMF was fluctuating between southward and northward. Figure 3a displays the electron fluxes measured by the LANL 1991-080 and 1990-095 satellites on 24 October 2002, and substorm onsets in the flux data are indicated by the vertical dotted lines. The periodic substorms occurred during the main phase and initial recovery stage of a magnetic storm. The period of the substorms was $\sim$3 hours. In Figure 3b, the solar wind pressure and IMF B_z data measured by the Wind and Geotail satellites are plotted. Wind was at (96, 10, 1) R_E GSM, and Geotail was at (29, 10, 0) R_E GSM. The solar wind pressure did not show any significant variations. The IMF B_z had a small amplitude and fluctuated between southward and northward for most times. Although the IMF B_z fluctuated very rapidly, the substorm onsets still occurred every $\sim$3 hours and did not follow the rapid IMF northward turnings.

[9] In order to show the details of the IMF B_z fluctuations, we plot in Figure 4 the LANL 1991-080 flux and Wind IMF B_z data between 1000 and 1800 UT on 24 October 2002. There were three substorm onsets at 1048, 1400, and 1650 UT. The changes in IMF B_z were rather large. For example, the change of the IMF B_z was 25 nT around 1215 UT. However, even such a big northward turning of the IMF did not trigger a substorm onset. The substorms onsets occurred successively every $\sim$3 hours at the time they should occur, no matter whether the IMF was continuously southward or fluctuating between southward and northward.

3. Discussion

[10] *Huang* [2002] and *Huang et al.* [2003a, 2003b] have shown that periodic substorms occur during stable IMF and suggested that the period of $\sim$3 hours in the substorms is determined by the magnetosphere. In this paper, we show for the first time that the period of substorms is still $\sim$3 hours during fluctuating IMF and that a sudden change in the solar wind does not necessarily cause a substorm onset. In the case of 18 April 2001 (Figure 2), the IMF B_z had been strongly southward ($-12 \sim -18$ nT) for 1.2 hours since the substorm onset at 0306 UT. It is surprising that a northward IMF turning with a change of 31 nT in the IMF B_z at 0418 UT was not able to trigger a substorm onset. A reasonable interpretation is that the magnetosphere at the moment was not in a state conducive to the generation of substorms. The observations provide a clue that the magnetosphere will take $\sim$3 hours after a substorm onset to reach the state unstable to substorms. A sudden change in the solar wind may provide an external perturbation to initiate an internal plasma instability in the magnetosphere, and the plasma instability will, through either a near-tail

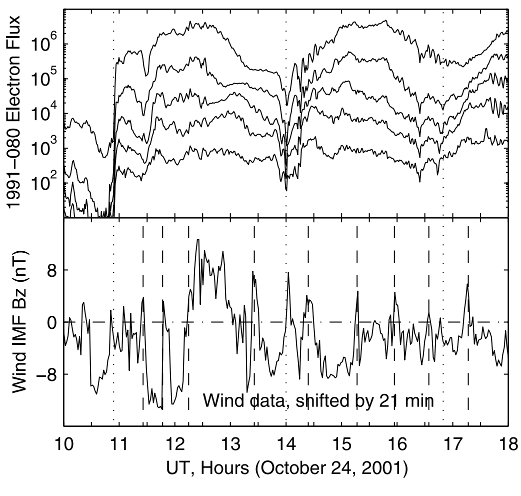

Figure 4. Electron fluxes measured by LANL 1991-080 and IMF B_z measured by Wind on 24 October 2002. The vertical dotted lines indicate flux injections (substorm onsets), and the vertical dashed lines indicate northward turnings of the IMF.

magnetic reconnection [*Hones*, 1984; *Baker et al.*, 1996] or a current disruption [*Lui*, 1996], result in the substorm onset. If the magnetospheric state is stable to the plasma instability, no substorms will occur, no matter whether the solar wind has a sudden change. On the other hand, if the magnetosphere has reached the unstable state, an internal plasma instability can trigger substorm onsets, even if there is no external triggering from the solar wind.

[11] Another important issue is whether the period of substorms is determined by the energy stored within the magnetosphere. Substorms have been explained as a process of energy loading and unloading (storage and release) in the magnetotail. The energy is transferred to the magnetosphere from the solar wind during the growth phase of a substorm, and the stored energy is released during the expansion phase. If the process of the energy storage and release has a time scale of ~3 hours, it explains the periodic occurrence of substorms. This scenario implies that the period of substorms depends on the magnitude of the southward IMF, because stronger southward IMF corresponds to larger energy transfer rate. The time for the magnetosphere to reach the maximum energy state should be shorter for stronger southward IMF than for weaker southward IMF. However, the observations appear to be inconsistent with this scenario. In the case of 18 April 2002, the merging rate between the IMF and magnetospheric magnetic field, defined as a function of $V_{sw}B_{zs}$, was about 2 times lager in the interval of 0200–1100 UT than that in the interval of 1200–2400 UT. However, the period of the substorms was slightly longer in the earlier interval than that in the later interval. Furthermore, the IMF B_z was small and fluctuating between southward and northward on 24 October 2002. The merging rate, as well as the energy transferred to the magnetosphere, was much larger on 18 April 2002 than on 24 October 2002. However the periods of the substorms were very close in the two cases. The results suggest that the period of substorms is not determined by the energy transferred to the magnetosphere from the solar wind.

4. Summary

[12] In this paper, we have presented the observations of two phenomena that were not reported previously. (1) A large northward turning of the IMF or a large solar wind pressure impulse after an interval of southward IMF does not necessarily trigger substorm onsets. In the case of 18 April 2001, the IMF B_z had been strongly negative ($-12 \sim -18$ nT) for 1.2 hours, and a northward IMF turning with a change of 31 nT in the IMF B_z did not trigger a substorm onset. (2) Periodic substorms can occur when the IMF B_z is small and fluctuating between southward and northward. The period of the substorms during the fluctuating IMF B_z is also ~3 hours, nearly the same as that during strongly southward IMF. In the cases of 24 October 2002, there were a number of northward turnings of the IMF between two successive substorm onsets. However, these fast northward turnings of the IMF did not cause corresponding substorm onsets.

[13] Another important phenomenon is that the period of the substorms does not depend on the magnitude of the IMF B_z. In the case of 18 April 2002, the IMF B_z was strongly and continuously negative. In contrast, the IMF B_z was small and fluctuating between southward and northward on 24 October 2002. The merging rate between the IMF and magnetospheric magnetic field and the energy transferred to the magnetosphere were much larger on 18 April 2002 than on 24 October 2002. However the periods of the substorms were very close in these two cases.

[14] The observations show that the period of substorms is neither determined directly by variations in the solar wind nor indirectly by the energy transferred to the magnetosphere from the solar wind. We suggest that a sudden change in the solar wind can trigger a substorm onset if and only if the magnetosphere has reached a state conducive to the generation of substorms. The observations provide a clue that the magnetosphere will take ~3 hours after a substorm onset to reach the state unstable to substorms. Otherwise, no substorms will occur, no matter whether the solar wind has a sudden change. In the case of no external triggering from the solar wind, substorms will still occur when the magnetosphere has reached the unstable state, and an internal plasma instability can trigger substorm onsets.

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